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Application of Wigner Distribution for the Detection of Accelerating Low-Altitude Aircraft using HF Surface-Wave Radar

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Defence R&D Canada

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Technical Report

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Abstract

Real radar data has been analysed using the Fourier transform method and the type-III Wigner distribution. The results show that whenever the target was detectable by the Fourier transform method, the target was also detectable by the smoothed type-III Wigner distribution method. In the other trials, the target was not detectable by the Fourier transform method but it was detectable by the smoothed type-III Wigner distribution method to varying degrees of success. Based on the analysis of real radar data, we conclude that the smoothed type-III Wigner distribution provides a promising method of detecting accelerating targets. However, more work needs to be done to find an optimum smoothing method. It may turn out that different smoothing methods have to be used depending on the acceleration and the closeness of the target to the clutter region. Another important contribution of the present work is the use of the type-III Wigner distribution rather than the type-I Wigner distribution which has been used by many other researchers. When the type-I Wigner distribution is used, the range of unambiguously measurable normalized velocities is π . Moreover, targets that are π radians away from the clutter region in the spectral domain will be masked by the clutter and cannot be detected. The type-III Wigner distribution helps us to overcome these problems. When the type-III Wigner distribution is used, the range of unambiguously measurable normalized velocities is 2π , and target that are π radians away from the clutter region can be detected.

Résumé

Des données radar réelles ont été analysées au moyen de la méthode de la transformée de Fourier et de la distribution de Wigner de type-III. Les résultats montrent que, lorsque la cible était détectable par la méthode de la transformée de Fourier, elle l'était aussi par la méthode de distribution de Wigner de type-III lissée. Dans les autres essais, la cible n'était pas détectable par la méthode de la transformée de Fourier, mais elle l'était par la méthode de distribution de Wigner de type-III lissée avec divers degrés de succès. L'analyse des données radar réelles permet de conclure que la distribution de Wigner de type-III lissée constitue une méthode prometteuse de détection des cibles en accélération. Il faudra cependant mener d'autres travaux pour trouver une méthode de lissage optimale. Il se peut qu'il faille utiliser différentes méthodes de lissage selon l'accélération de la cible et sa proximité de la région de clutter. Une autre contribution importante des travaux en cours est l'utilisation de la distribution de Wigner de type-III de préférence à la distribution de Wigner de type-I, dont de nombreux autres chercheurs se sont servi. Lorsque la distribution de Wigner de type-I est utilisée, la fourchette des vitesses normalisées mesurables non ambiguës est π . En outre, les cibles à π radians de la région de clutter dans le domaine spectral seront masquées par le clutter, d'où impossibilité de les détecter. La distribution de Wigner de type-III permet de surmonter ces problèmes. Lorsque la distribution de Wigner de type-III est utilisée, la fourchette des vitesses normalisées mesurables non ambiguës est 2π , et les cibles à π radians de la région de clutter peuvent être détectées.

Executive summary

One of the central problems in High Frequency (HF) radar data is the analysis of a time series. The Fourier transform method, or Doppler processing method, has been generally used in HF radar to detect targets that are moving with constant radial acceleration. Examples of accelerating targets are manoeuvring aircrafts and missiles. Thayaparan and Yasotharan [1] show that there are limitations and shortcomings in the Fourier transform method to detect accelerating targets because of the phenomenon known as Doppler smearing. They show that when the target is constantly accelerating, the Fourier method may still be used to detect the target and estimate its median velocity, provided the acceleration is small enough in the sense to be described in this report. It is shown that for a given acceleration, the number of pulses cannot be increased indefinitely without resulting in catastrophic failure of the method. Conversely, for a given number of pulses, the acceleration cannot be arbitrarily large without resulting in catastrophic failure of the method. Thus the number of pulses and the acceleration have to be matched to achieve optimum performance [1].

Consequently, for the interpretation of radar data in terms of a changing frequency content, we need a representation of our data as a function of both time and frequency. The purpose of this report is therefore to stress the importance of alternative methods which have received little attention in the past, namely, the joint time-frequency representation of signals. In this report, we choose the Wigner distribution, together with a ambiguity function, as the basic tools, since both possess some important properties which make them very attractive for time-frequency signal analysis [2].

Real HF radar data has been analysed using the Fourier transform method and the type-III Wigner distribution. The results show that whenever the target was detectable by the Fourier transform method, the target was detectable also by the smoothed type-III Wigner distribution method. In the other trials the target was not detectable by the Fourier transform method but the target was detectable by the smoothed type-III Wigner distribution method to varying degrees of success. Based on the analysis of real radar data, we conclude that the smoothed type-III Wigner distribution provides a promising method of detecting accelerating targets. However, more work has to be done to find an optimum smoothing method. It may turn out that different smoothing methods have to be used depending on the acceleration and the closeness of the target to the clutter region. Another important contribution of the present work is the use of the type-III Wigner distribution rather than the type-I Wigner distribution which has been used by many other researchers. When the type-I Wigner distribution is used, the range of unambiguously measurable normalized velocities is π . Moreover, targets that are π radians away from the clutter region in the spectral domain be masked by the clutter and cannot be detected. The type-III Wigner distribution helps us to overcome these problems. When the type-III Wigner distribution is used, the range of unambiguously measurable normalized velocities is 2π , and target that are π radians away from the clutter region can be detected.

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Sommaire

Un des principaux problèmes éprouvé avec les données de radar haute fréquence (HF) est l'analyse d'une série chronologique. La méthode à transformée de Fourier, ou la méthode de traitement Doppler, a généralement été utilisée dans le radar HF pour la détection des cibles à accélération radiale constante. Les cibles présentant une accélération sont, par exemple, les avions qui effectuent des manœuvres et les missiles. Thayaparan et Yasotharan [1] montrent que la méthode à transformée de Fourier comporte des limites et des lacunes pour la détection des cibles à accélération, en raison du phénomène appelé la persistance Doppler. Ils montrent que dans le cas d'une cible à accélération constante, la méthode de Fourier peut encore être appliquée pour détecter la cible et estimer sa vitesse médiane, à condition que l'accélération soit assez faible dans le contexte du présent rapport. On montre que pour une accélération donnée, le nombre d'impulsions ne peut pas être augmenté indéfiniment sans qu'il en résulte un échec catastrophique de la méthode. Inversement, pour un nombre donné d'impulsions, l'accélération ne peut pas augmenter arbitrairement sans qu'il en résulte aussi un échec catastrophique de la méthode. Ainsi, le nombre d'impulsions et l'accélération doivent être adaptés pour permettre des performances optimales [1].

Par conséquent, pour interpréter les données radar du point de vue d'un contenu en fréquences variable, nous devons les représenter aussi bien en fonction du temps qu'en fonction de la fréquence. L'objet du présent rapport est donc de souligner l'importance des méthodes de rechange auxquelles on a accordé peu d'attention par le passé, notamment la représentation temps-fréquence combinée des signaux. Dans le rapport, nous choisissons la distribution de Wigner avec une fonction d'ambiguïté comme outil de base, étant donné que ces deux éléments offrent certaines propriétés importantes qui présentent un grand intérêt pour l'analyse temps-fréquence des signaux [2].

Des données radar HF réelles ont été analysées au moyen de la méthode de la transformée de Fourier et de la distribution de Wigner de type-III. Les résultats montrent que, lorsque la cible était détectable par la méthode de la transformée de Fourier, elle l'était aussi par la méthode de distribution de Wigner de type-III lissée. Lors des autres essais, la cible n'était pas détectable par la méthode de la transformée de Fourier, mais elle l'était par la méthode de distribution de Wigner de type-III lissée avec divers degrés de succès. L'analyse des données radar réelles permet de conclure que la distribution de Wigner de type-III lissée constitue une méthode prometteuse de détection des cibles en accélération. Il faudra cependant mener d'autres travaux pour trouver une méthode de lissage optimale. Il se peut qu'il faille utiliser différentes méthodes de lissage selon l'accélération de la cible et sa proximité de la région de clutter. Une autre contribution importante des travaux en cours est l'utilisation de la distribution de Wigner de type-III de préférence à la distribution de Wigner de type-I, dont de nombreux autres chercheurs se sont servi. Lorsque la distribution de Wigner de type-I est utilisée, la fourchette des vitesses normalisées mesurables non ambiguës est π . En outre, les cibles à π radians de la région de clutter dans le domaine spectral seront masquées par le clutter, d'où impossibilité de les détecter. La distribution de

Wigner de type-III permet de surmonter ces problèmes. Lorsque la distribution de Wigner de type-III est utilisée, la fourchette des vitesses normalisées mesurables non ambiguës est 2π , et les cibles à π radians de la région de clutter peuvent être détectées

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1. Introduction

The Fourier Transform is at the heart of a wide range of techniques that are used in HF radar data analysis and processing. Mapping the data into the temporal frequency domain is an effective way of recording the data such that their global characteristics can be assessed. However, the change of frequency content with time is one of the main features we observe in HF radar data. Because of this change of frequency content with time, radar signals belong to the class of non-stationary signals.

One of the central problems in High Frequency radar data is the analysis of a time series. The Fourier transform method, or Doppler processing method, has been generally used in HF radar to detect targets that are moving with constant radial acceleration. Examples of accelerating targets are manoeuvring aircraft and missiles. Thayaparan and Yasotharan [1] show that there are limitations and shortcomings in the Fourier transform method to detect accelerating targets because of the phenomenon known as Doppler smearing. They show that when the target is constantly accelerating, the Fourier method may still be used to detect the target and estimate its median velocity, provided the acceleration is small enough in the sense to be described in the paper. It is shown that for a given acceleration, the number of pulses cannot be increased indefinitely without resulting in catastrophic failure of the method. Conversely, for a given number of pulses, the acceleration cannot be arbitrarily large without resulting in catastrophic failure of the method. Thus the number of pulses and the acceleration have to be matched to achieve optimum performance [1].

Consequently, for the interpretation of radar data in terms of a changing frequency content, we need a representation of our data as a function of both time and frequency. The purpose of this paper is therefore to stress the importance of alternative methods which have had little attention in the past, namely, the joint time-frequency representation of signals. In this report, we use the new discrete-time Wigner time-frequency distribution. This distribution was independently derived by the authors Thayananthan and Yasotharan [3]. But it had already been derived by Chan [4] in an effort to solve the problem of aliasing. Nevertheless, the optimality properties of this discrete-time Wigner distribution for signal detection were not observed in [4]. Therefore, in the context of signal detection, this discrete-time Wigner distribution seems new.

2. Signal Model

In this study, the radar is assumed to be of the Pulse Doppler type, that is, it sends out a uniform train of RF pulses and phase-coherently receives their returns. It is also assumed that the receiver has pulse compression capability so that a pulse return from an isolated target can be represented by a single sample of the compressed pulse.

2.1 Single-Target Scenario

Suppose the radar sends out N pulses, one every T seconds, and there is a target moving with constant radial acceleration. Assume that the range walk is negligible, that is, the change in range during the observation period of NT seconds is negligible compared to the radar range resolution as determined by the width of the compressed pulse. Then the samples of the N range-compressed pulses taken at the range of the target have the form

$$(1) \quad r(n) = s(n) + v(n), \quad \text{for } n = 0, 1, 2, 3, \dots, (N-1),$$

where

$$(2) \quad s(n) = ae^{j(b_0 + b_1 n + \frac{1}{2} b_2 n^2)},$$

is the noise-free signal, and $v(n)$ is a sequence of independently and identically distributed (iid) samples of complex Gaussian noise with mean zero and variance σ^2 .

The signal parameters a and b_0 are the target amplitude and phase respectively. The signal parameters b_1 and b_2 are the normalized initial radial velocity and the normalized radial acceleration respectively.

2.1.1 Normalized Initial Velocity and Acceleration

The normalized initial radial velocity is defined as

$$(3) \quad b_1 = u \left(\frac{4\pi T}{\lambda} \right)$$

where u is the initial radial velocity in meters/sec, T is pulse repetition interval in secs, and λ is the carrier wavelength in meters. Similarly, the normalized radial acceleration is defined as

$$(4) \quad b_2 = f \left(\frac{4\pi T^2}{\lambda} \right)$$

where f is the radial acceleration in meters/sec/sec towards the radar. It can be seen that both of the above normalized quantities are non-dimensional.

To obtain these relations note that the increment in range d , measured from the beginning of the observation interval, as a function of continuous-time t , is $d(t) = ut + \frac{1}{2}ft^2$, and therefore the phase increment of a pulse as a function of discrete-time, or pulse index, is given by

$$(5) \quad 2\pi \left(\frac{2d(nT)}{\lambda} \right) = \frac{4\pi}{\lambda} \left(unT + \frac{1}{2}fn^2T^2 \right),$$

$$(6) \quad = u \left(\frac{4\pi T}{\lambda} \right) n + \frac{1}{2}f \left(\frac{4\pi T^2}{\lambda} \right) n^2.$$

In the rest of the discussion, the term *velocity* and *acceleration* refer to *normalized radial velocity* and *normalized radial acceleration* respectively.

2.1.2 Per-Pulse Signal-to-Noise Ratio

The Per-Pulse Signal-to-Noise Ratio is defined as

$$(7) \quad \text{SNR}_{\text{pulse}} = \left(\frac{a}{\sigma} \right)^2.$$

The performance measures of any detection method will depend on $\text{SNR}_{\text{pulse}}$ and the number of pulses N . The values of the signal parameters b_1 and b_2 may also influence performance. We are interested in detection methods whose performance will increase as N increases regardless of the values of b_1 and b_2 .

2.2 Multiple-Target Scenario - Targets Separated in Range

When there are multiple targets, as long as they are separated from one another in range by at least the radar range resolution as determined by the width of the compressed pulse, a model of the above form will be valid for each of them.

Thus, if there are two targets separated in range, the samples of the N range-compressed pulses taken at the corresponding ranges of the targets have the form

$$(8) \quad r_1(n) = s_1(n) + v_1(n), \text{ and}$$

$$(9) \quad r_2(n) = s_2(n) + v_2(n) \quad \text{for } n = 0, 1, 2, 3, \dots, (N-1),$$

where $s_1(n)$ and $s_2(n)$ are the noise-free signals, and $v_1(n)$ and $v_2(n)$ are sequences of independently and identically distributed samples of complex Gaussian noise with mean zero and variance σ^2 .

Because of the independence of $v_1(n)$ and $v_2(n)$, the model decouples into two single target models

2.3 Multiple-Target Scenario - Targets Coincident in Range

When there are multiple targets coincident in range, the samples of the N range-compressed pulses taken at the range of the targets have the form

$$(10) \quad r(n) = s(n) + v(n), \quad \text{for } n = 0, 1, 2, 3, \dots, (N-1),$$

where $s(n)$ is the combined noise-free signal due to all targets and $v(n)$ is a sequence of independently and identically distributed samples of complex Gaussian noise with mean zero and variance σ^2 . If there are K targets, the combined noise-free signal has the form

$$(11) \quad s(n) = \sum_{k=1}^K a_k e^{j(b_{k,0} + b_{k,1}n + \frac{1}{2}b_{k,2}n^2)},$$

where a_k and $b_{k,0}$ are the amplitude and phase respectively of the k^{th} target, and $b_{k,1}$ and $b_{k,2}$ are the normalized initial radial velocity and the normalized radial acceleration respectively of the k^{th} target.

3. A Wigner Distribution Formulation for a Discrete-Time Chirp Signal

It is nearly 20 years ago that the Wigner distribution (also known as Wigner-Ville distribution) was given a prominent place in the signal processing community's spectrum of research interests. Recognition was given almost immediately for the potential of the Wigner distribution as a tool for displaying and analyzing signal characteristics in the time-frequency plane. This assessment was soundly supported by the long list of desirable mathematical properties, such as correct marginal and support properties, satisfied by the Wigner distribution. Unlike the spectrogram, for instance, the resolution of the Wigner distribution is not limited by the temporal or spectral properties of a window, since a window is not required in the definition of the Wigner distribution [3,5]

On the other hand, due to its high resolution and its quadratic nature, the Wigner distribution locally exhibits oscillations between positive and negative values to an extent that smoothing, in a certain sense in accordance with the Heisenberg uncertainty principle, is necessary to make it non-negative everywhere [6]. As a consequence, a pointwise interpretation of the Wigner distribution as a true probability density function is not possible. This circumstance has kept the discussions in the signal processing community quite animated, yielding all sorts of modified Wigner distributions through the design of smoothing kernels and distributions involving the signals in a non-quadratic way. Thus, to a large extent, the interest and research effort of the community has been directed at redefining and re-interpreting the Wigner distribution, with the purpose of obtaining a clear and useful display and analysis tool.

Besides being a useful display and analysis tool, the Wigner distribution can be a great help in the design of time-frequency filtering methods. In this section and the following sections, we develop such methods for the detection of aircraft from the noisy signals. The Wigner distribution was originally defined for continuous-time signals. A discrete-time version of it was proposed recently. Unfortunately, this discrete-time Wigner distribution suffers from aliasing effects, which prevent several of the properties of the continuous-time Wigner distribution from carrying over straightforwardly. In this report, a discrete-time Wigner distribution which does not suffer from aliasing is introduced. It is essentially an augmentation of the previous version, incorporating new information about the signal not contained in the previous version.

3.1 Three Definitions of Wigner Distribution for Discrete-Time Signals

Given a discrete-time signal $r(n)$, we consider three definitions of auto time-frequency distributions which have some properties analogous to those of the classical Wigner distribution defined for continuous-time signals [7].

It is straightforward to verify that these are real-valued functions

3.1.1 Type-I Wigner Distribution

The type-I Wigner distribution $W_r^I(n, \theta)$ is defined as

$$(12) \quad W_r^I(n, \theta) = \sum_k r(n+k)r^*(n-k)e^{-j2k\theta},$$

where n is integer-valued and θ is real-valued. Note that this is the same as the definition provided in [7] except for the missing scaling factor 2 at the front

It is easy to verify that the type-I Wigner distribution is a periodic function of θ with period π . This property are discussed more in the following subsections

For a signal $r(n)$ that is zero outside $0 \leq n \leq (N-1)$, the type-I Wigner distribution is zero outside $0 \leq n \leq (N-1)$

3.1.2 Type-II Wigner Distribution

The type-II Wigner distribution $W_r^{II}(n, \theta)$ is defined as

$$(13) \quad W_r^{II}(n, \theta) = \sum_k r(n+k+1)r^*(n-k)e^{-j(2k+1)\theta},$$

where n is integer-valued and θ is real-valued

It is straight forward to verify that the type-II Wigner distribution is a periodic function of θ with period 2π . It is also straight forward to verify that

$$(14) \quad W_r^{II}(n, \theta + \pi) = -W_r^{II}(n, \theta).$$

These properties are discussed more in the following subsections

For a signal $r(n)$ that is zero outside $0 \leq n \leq (N-1)$, the type-II Wigner distribution is zero outside $0 \leq n \leq (N-2)$

3.1.3 Type-III Wigner Distribution

The type-III Wigner distribution $W_r^{III}(n, \theta)$ is defined in terms of the type-I and type-II Wigner distributions as follows

$$(15) \quad W_r^{III}(n, \theta) = \begin{cases} W_r^I(n/2, \theta) & \text{for even } n, \\ W_r^{II}((n-1)/2, \theta) & \text{for odd } n. \end{cases}$$

It is straight forward to verify that the type-III Wigner distribution is a periodic function of θ with period 2π . This property is discussed more in the following subsections

For a signal $r(m)$ that is zero outside $0 \leq m \leq (N-1)$, the type-III Wigner distribution is zero outside $0 \leq n \leq 2(N-1)$. However, if we consider even n to correspond to integer values of time and odd n to correspond to half-integer values of time then the type-III Wigner distribution is zero outside the time range $0 \leq m \leq (N-1)$

3.2 The Range of Unambiguously Measurable Velocities of the Type-I and Type-III Wigner Distribution Based Methods

As shown in Section 3.1.1, the period of the type-I Wigner distribution is π . Therefore the signals

$$(16) \quad ae^{j(b_0 + b_1 n + \frac{1}{2} b_2 n^2)}, \text{ and}$$

$$(17) \quad ae^{j(\tilde{b}_0 + (b_1 + \pi)n + \frac{1}{2} b_2 n^2)},$$

gives rise to the same type-I Wigner distribution. In other words, if we detect, using the type-I Wigner distribution, the presence of a signal in the time-frequency plane with intercept and slope parameters c_1 and c_2 respectively, then we cannot resolve the ambiguity as to whether the physical signal was

$$(18) \quad ae^{j(c_0 + c_1 n + \frac{1}{2} c_2 n^2)}, \text{ or}$$

$$(19) \quad ae^{j(c_0 + (c_1 + \pi)n + \frac{1}{2} c_2 n^2)}$$

without external information

In contrast, as shown in Section 3.1.3, the period of the type-III Wigner distribution is 2π . Therefore the signals

$$(20) \quad ae^{j(b_0 + b_1 n + \frac{1}{2} b_2 n^2)}, \text{ and}$$

$$(21) \quad ae^{j(\tilde{b}_0 + (b_1 + \pi)n + \frac{1}{2} b_2 n^2)},$$

give rise to different type-III Wigner distributions.

If we detect, using the type-III Wigner distribution, the presence of a signal in the time-frequency plane with intercept and slope parameters c_1 and c_2 respectively, then there is no ambiguity as to whether the physical signal was

$$(22) \quad ae^{j(c_0 + c_1 n + \frac{1}{2} c_2 n^2)}, \text{ or}$$

$$(23) \quad ae^{j(c_0 + (c_1 + \pi)n + \frac{1}{2} c_2 n^2)}.$$

However we need external information to resolve the ambiguity as to whether the physical signal was

$$(24) \quad ae^{j(c_0 + c_1 n + \frac{1}{2} c_2 n^2)}, \text{ or}$$

$$(25) \quad ae^{j(c_0 + (c_1 + 2\pi)n + \frac{1}{2} c_2 n^2)}.$$

3.3 The Wigner Distributions of the Discrete-Time Chirp Signal

In this sub-section we derive the type-I, type-II, and type-III Wigner distributions for the discrete-time chirp signal

$$(26) \quad s(n) = ae^{j(b_0 + b_1 n + \frac{1}{2} b_2 n^2)}, \text{ for } n = 0, 1, \dots, (N-1),$$

defined in Section 2. These derivations have been done in Appendix A assuming $a = 1$. The results stated here are obtained by scaling those derived in the appendix by a^2 . Note that the Wigner distributions do not depend on b_0 .

3.3.1 The Type-I Wigner Distribution of $s(n)$

The Type-I Wigner Distribution $W_s^I(n, \theta)$ of $s(n)$ is given by

$$(27) \quad W_s^I(n, \theta) = a^2 \begin{cases} \frac{2 \min(n, N-1-n) + 1}{\sin[(\theta - (b_1 + b_2 n))(2 \min(n, N-1-n) + 1)]} & \text{if } \theta = b_1 + b_2 n \bmod \pi, \\ \frac{1}{\sin[\theta - (b_1 + b_2 n)]} & \text{otherwise.} \end{cases}$$

for $0 \leq n \leq (N - 1)$, and it is zero outside this range

In a 3-dimensional plot [3], it has a ridge along the lines given by

$$(28) \quad \theta = b_1 + b_2 n \bmod \pi.$$

The height of the ridge is given by

$$(29) \quad 2 \min(n, N - 1 - n) + 1.$$

3.3.2 The Type-II Wigner distribution of $s(n)$

The Type-II Wigner Distribution $W_s^{II}(n, \theta)$ of $s(n)$ is given by

$$(30) \quad W_s^{II}(n, \theta) = a^2 \begin{cases} 2 \min(n, N - 2 - n) + 2 & \text{if } \theta = b_1 + \frac{1}{2}b_2 + b_2 n \bmod 2\pi, \\ -(2 \min(n, N - 2 - n) + 2) & \text{if } \theta = \pi + b_1 + \frac{1}{2}b_2 + b_2 n \bmod 2\pi, \\ \frac{\sin[(\theta - (b_1 + \frac{1}{2}b_2 + b_2 n))(2 \min(n, N - 2 - n) + 2)]}{\sin[\theta - (b_1 + \frac{1}{2}b_2 + b_2 n)]} & \text{otherwise.} \end{cases}$$

for $0 \leq n \leq (N - 2)$, and it is zero outside this range.

In a 3-dimensional plot [3], it has a ridge along the lines given by

$$(31) \quad \theta = b_1 + \frac{1}{2}b_2 + b_2 n \bmod 2\pi.$$

The height of the ridge is given by

$$(32) \quad 2 \min(n, N - 2 - n) + 2.$$

In a 3-dimensional plot, it also has a valley along the lines given by

$$(33) \quad \theta = \pi + b_1 + \frac{1}{2}b_2 + b_2 n \bmod \pi.$$

The depth of the valley is given by

$$(34) \quad 2 \min(n, N - 2 - n) + 2.$$

3.3.3 The Type-III Wigner distribution of $s(n)$

The Type-III Wigner Distribution $W_s^{III}(n, \theta)$ of $s(n)$ is given by

$$W_s^{III}(n, \theta) = a^2 \begin{cases} 2 \min(\frac{n}{2}, N - 1 - \frac{n}{2}) + 1 & \text{if } \theta = b_1 + \frac{1}{2}b_2n \bmod 2\pi, \\ (-1)^n [2 \min(\frac{n}{2}, N - 1 - \frac{n}{2}) + 1] & \text{if } \theta = \pi + b_1 + \frac{1}{2}b_2n \bmod 2\pi, \\ \frac{\sin[(\theta - (b_1 + \frac{1}{2}b_2n))(2 \min(\frac{n}{2}, N - 1 - \frac{n}{2}) + 1)]}{\sin[\theta - (b_1 + \frac{1}{2}b_2n)]} & \text{otherwise.} \end{cases} \quad (35)$$

for $0 \leq n \leq 2(N - 1)$, and it is zero outside this range

In a 3-dimensional plot [3], it has a ridge along the lines given by

$$\theta = b_1 + \frac{1}{2}b_2n \bmod 2\pi. \quad (36)$$

The height of the ridge is given by

$$\min(n, 2(N - 1) - n) + 1. \quad (37)$$

In a 3-dimensional plot, it also has an oscillatory structure along the lines give by

$$\theta = \pi + b_1 + \frac{1}{2}b_2n \bmod 2\pi. \quad (38)$$

The period of the oscillation is one unit and the amplitude of the oscillation is given by

$$\min(n, 2(N - 1) - n) + 1. \quad (39)$$

4. An Ambiguity Function Formulation for a Discrete-Time Chirp Signal

The inverse Fourier transform of the Wigner distribution is called the ambiguity function (AF). The Fourier transform maps the Wigner distribution auto-components to a region centered on the region of the AF plane, whereas it maps the oscillatory Wigner distribution cross-components away from the origin [8].

The fact that the auto- and cross-components are spatially separated in the AF domain means that if we apply mask function to the AF, we can suppress some of the cross-components. This masking operation defines a new time-frequency representation (TFR).

$$(40) \quad \text{TFR} = \text{Fourier transform}\{\text{AF} \cdot \text{Kernel}\}$$

with properties different from the Wigner distribution. The mask function is called the 'kernel' of the TFR. Since there are many possible 2-dimensional kernel functions, there exist many different TFRs for the same signal. The class of all TFRs obtained in this fashion is called Cohen's class. A more detailed description of the ambiguity function is given [8].

4.1 Three Definitions of Ambiguity Function for Discrete-Time Signals

Given a discrete-time signal $r(n)$, we consider three definitions of ambiguity function which are related, via a two-dimensional Fourier transformation, to the three definitions of Wigner distribution given in Section 3.1.

4.1.1 Type-I Ambiguity Function

The type-I ambiguity function $A_r^I(k, \alpha)$ is defined as

$$(41) \quad A_r^I(k, \alpha) = \sum_m r(m+k)r^*(m-k)e^{j2m\alpha},$$

where k is integer-valued and α is real-valued.

For a signal $r(n)$ that is zero outside $0 \leq n \leq (N-1)$, the type-I ambiguity function is zero outside $-\text{floor}\left(\frac{N-1}{2}\right) \leq k \leq \text{floor}\left(\frac{N-1}{2}\right)$.

4.1.2 Type-II Ambiguity Function

The type-II ambiguity function $A_r^{II}(k, \alpha)$ is defined as

$$(42) \quad A_r^{II}(k, \alpha) = \sum_m r(m+k+1)r^*(m-k)e^{j(2m+1)\alpha},$$

where k is integer-valued and α is real-valued

For a signal $r(n)$ that is zero outside $0 \leq n \leq (N-1)$, the type-II ambiguity function is zero outside $-\text{floor}\left(\frac{N}{2}\right) \leq k \leq \text{floor}\left(\frac{N-2}{2}\right)$.

4.1.3 Type-III Ambiguity Function

The type-III ambiguity function $A_r^{III}(k, \alpha)$ is defined in terms of the type-I and type-II ambiguity functions as follows

$$(43) \quad A_r^{III}(k, \alpha) = \begin{cases} A_r^I(k/2, \alpha) & \text{for even } k, \\ A_r^{II}((k-1)/2, \alpha) & \text{for odd } k. \end{cases}$$

For a signal $r(n)$ that is zero outside $0 \leq n \leq (N-1)$, the type-III ambiguity function is zero outside $-(N-1) \leq k \leq (N-1)$.

4.1.4 Cross Ambiguity Functions Between Two Discrete-Time Signals

Given discrete-time signals $x(n)$ and $y(n)$, we can define cross ambiguity functions as straightforward extensions of the definitions given above. Thus

$$(44) \quad A_{x,y}^I(k, \alpha) = \sum_m x(m+k)y^*(m-k)e^{j2m\alpha},$$

$$(45) \quad A_{x,y}^{II}(k, \alpha) = \sum_m x(m+k+1)y^*(m-k)e^{j(2m+1)\alpha},$$

$$(46) \quad A_{x,y}^{III}(k, \alpha) = \begin{cases} A_{x,y}^I(k/2, \alpha) & \text{for even } k, \\ A_{x,y}^{II}((k-1)/2, \alpha) & \text{for odd } k. \end{cases}$$

4.2 The Ambiguity Functions of a Discrete-Time Chirp Signal

In this sub-section we derive the type-I, type-II, and type-III ambiguity functions of the discrete-time chirp signal

$$(47) \quad s(n) = \begin{cases} e^{j(b_1 n + \frac{1}{2} b_2 n^2)} & \text{if } 0 \leq n \leq (N-1) \\ 0 & \text{otherwise.} \end{cases}$$

4.2.1 Type-I Ambiguity Function

Recall that the type-I ambiguity function $A_s^I(k, \alpha)$ is defined as

$$(48) \quad A_s^I(k, \alpha) = \sum_m s(m+k) s^*(m-k) e^{j2m\alpha},$$

where k is integer-valued and α is real-valued

It is straight forward to see that the signal product term $s(m+k) s^*(m-k)$ is zero outside the ranges $-\text{floor}(\frac{N-1}{2}) \leq k \leq \text{floor}(\frac{N-1}{2})$ and $\max(k, -k) \leq m \leq N-1 - \max(k, -k)$

Thus, for $-\text{floor}(\frac{N-1}{2}) \leq k \leq \text{floor}(\frac{N-1}{2})$, we have

$$(49) \quad A_s^I(k, \alpha) = e^{j2b_1 k} \sum_{m=\max(k, -k)}^{N-1-\max(k, -k)} e^{j2(b_2 k + \alpha)m},$$

which is a sum of a geometric series that can be evaluated as

$$(50) \quad A_s^I(k, \alpha) = \begin{cases} e^{j2b_1 k} (N - 2 \max(k, -k)) & \text{if } b_2 k + \alpha = 0 \bmod \pi, \\ e^{j2b_1 k} e^{j[(b_2 k + \alpha)(N-1)]} \left(\frac{\sin[(b_2 k + \alpha)(N - 2 \max(k, -k))]}{\sin[(b_2 k + \alpha)]} \right) & \text{otherwise.} \end{cases}$$

4.2.2 Type-II Ambiguity Function

Recall that the type-II ambiguity function $A_s^{II}(k, \alpha)$ is defined as

$$(51) \quad A_s^{II}(k, \alpha) = \sum_m s(m+k+1) s^*(m-k) e^{j(2m+1)\alpha},$$

where k is integer-valued and α is real-valued

It can be seen that the signal product term $s(m+k+1)s^*(m-k)$ is zero outside the ranges $-\text{floor}(\frac{N}{2}) \leq k \leq \text{floor}(\frac{N-2}{2})$ and $\max(k, -(k+1)) \leq m \leq N-2-\max(k, -(k+1))$

Thus, for $-\text{floor}(\frac{N}{2}) \leq k \leq \text{floor}(\frac{N-2}{2})$, we have

$$(52) A_s^{II}(k, \alpha) = e^{j(b_1 + \frac{1}{2}b_2)(2k+1)} e^{j\alpha} \sum_{m=\max(k, -(k+1))}^{N-2-\max(k, -(k+1))} e^{j2(b_2(k+\frac{1}{2})+\alpha)m},$$

which is a sum of a geometric series that can be evaluated as

$$(53) A_s^{II}(k, \alpha) = \begin{cases} e^{j2b_1(k+\frac{1}{2})(N-1-2\max(k, -(k+1)))} & \text{if } b_2(k+\frac{1}{2}) + \alpha = 0 \bmod 2\pi, \\ e^{j2b_1(k+\frac{1}{2})} e^{j[(b_2(k+\frac{1}{2})+\alpha)(N-1)]} \left(\frac{\sin[(b_2(k+\frac{1}{2})+\alpha)(N-1-2\max(k, -(k+1)))]}{\sin[(b_2(k+\frac{1}{2})+\alpha)]} \right) & \text{other} \end{cases}$$

4.2.3 Type-III Ambiguity Function

Recall that the type-III ambiguity function $A_s^{III}(k, \alpha)$ is defined in terms of the type-I and type-II ambiguity functions as

$$(54) A_s^{III}(k, \alpha) = \begin{cases} A_s^I(k/2, \alpha) & \text{for even } k, \\ A_s^{II}((k-1)/2, \alpha) & \text{for odd } k. \end{cases}$$

Thus for $-(N-1) \leq k \leq (N-1)$,

$$(55) A_s^{III}(k, \alpha) = \begin{cases} e^{jb_1k(N-\max(k, -k))} & \text{if } \frac{1}{2}b_2k + \alpha = 0 \bmod \\ e^{jb_1k} e^{j[(\frac{1}{2}b_2k+\alpha)(N-1)]} \left(\frac{\sin[(\frac{1}{2}b_2k+\alpha)(N-\max(k, -k))]}{\sin[(\frac{1}{2}b_2k+\alpha)]} \right) & \text{otherwise.} \end{cases}$$

4.3 The Cross Ambiguity Functions of Two Discrete-Time Chirp Signals

In this sub-section we derive the type-I, type-II, and type-III cross ambiguity functions of the discrete-time chirp signals

$$(56) \quad x(n) = \begin{cases} e^{j(a_1 n + \frac{1}{2} a_2 n^2)} & \text{if } 0 \leq n \leq (N-1) \\ 0 & \text{otherwise} \end{cases},$$

$$(57) \quad y(n) = \begin{cases} e^{j(b_1 n + \frac{1}{2} b_2 n^2)} & \text{if } 0 \leq n \leq (N-1) \\ 0 & \text{otherwise} \end{cases}$$

4.3.1 Type-I Cross Ambiguity Function

Recall that the type-I cross ambiguity function $A_{x,y}^I(k, \alpha)$ is defined as

$$(58) \quad A_{x,y}^I(k, \alpha) = \sum_m x(m+k) y^*(m-k) e^{j2m\alpha},$$

where k is integer-valued and α is real-valued.

It is straight forward to see that the signal product term $x(m+k)y^*(m-k)$ is zero outside the ranges $-\text{floor}(\frac{N-1}{2}) \leq k \leq \text{floor}(\frac{N-1}{2})$ and $\max(k, -k) \leq m \leq N-1 - \max(k, -k)$

Defining

$$(59) \quad a_1 + b_1 = c_1,$$

$$(60) \quad a_2 + b_2 = c_2,$$

$$(61) \quad a_1 - b_1 = d_1,$$

$$(62) \quad a_2 - b_2 = d_2,$$

we can show

$$(63) \quad A_{x,y}^I(k, \alpha) = e^{j(c_1 k + \frac{1}{2} d_2 k^2)} \sum_{m=\max(k, -k)}^{N-1-\max(k, -k)} e^{j((d_1 + c_2 k + 2\alpha)m + \frac{1}{2} d_2 m^2)},$$

$$\text{for } -\text{floor}(\frac{N-1}{2}) \leq k \leq \text{floor}(\frac{N-1}{2})$$

Special Case $d_2 = 0$

$$A_{x,y}^I(k, \alpha) = \begin{cases} e^{jc_1 k(N - 2 \max(k, -k))} & \text{if } d_1 + c_2 k + 2\alpha = 0 \bmod \pi, \\ e^{jc_1 k} e^{j[\frac{1}{2}(d_1 + c_2 k + 2\alpha)(N-1)]} \left(\frac{\sin[\frac{1}{2}(d_1 + c_2 k + 2\alpha)(N - 2 \max(k, -k))]}{\sin[\frac{1}{2}(d_1 + c_2 k + 2\alpha)]} \right) & \text{otherwise.} \end{cases} \quad (64)$$

Thus $|A_{x,y}^I(k, \alpha)|$ is concentrated along the line $d_1 + c_2 k + 2\alpha = 0$ and symmetrically spread about it with respect to α . For a fixed k , the amount of spread with respect to α can be measured by $1/(N - 2 \max(k, -k))$

The General Case

Although it seems difficult to evaluate $A_{x,y}^I(k, \alpha)$ in the general case, by writing

$$A_{x,y}^I(k, \alpha) = e^{j(c_1 k + \frac{1}{2} d_2 k^2)} e^{j((d_1 + \frac{1}{2} d_2 (\frac{N-1}{2}) + c_2 k + 2\alpha)(\frac{N-1}{2}))} \sum_{m=\max(k, -k)}^{N-1-\max(k, -k)} e^{j((d_1 + d_2 (\frac{N-1}{2}) + c_2 k + 2\alpha)(m - (\frac{N-1}{2})) + \frac{1}{2} d_2 (m - (\frac{N-1}{2}))^2)}, \quad (65)$$

we can see that $|A_{x,y}^I(k, \alpha)|$ is symmetrically spread about the line $d_1 + d_2 (\frac{N-1}{2}) + c_2 k + 2\alpha = 0$ with respect to α . For small d_2 , $|A_{x,y}^I(k, \alpha)|$ is concentrated along the same line. For a fixed k , the amount of spread with respect to α will depend on both $(N - 2 \max(k, -k))$ and d_2 .

4.3.2 Type-II Cross Ambiguity Function

Recall that the type-II cross ambiguity function $A_{x,y}^{II}(k, \alpha)$ is defined as

$$A_{x,y}^{II}(k, \alpha) = \sum_m x(m + k + 1) y^*(m - k) e^{j(2m+1)\alpha}, \quad (66)$$

where k is integer-valued and α is real-valued

It is straight forward to see that the signal product term $x(m + k + 1) y^*(m - k)$ is zero outside the ranges $-\text{floor}(\frac{N}{2}) \leq k \leq \text{floor}(\frac{N-2}{2})$ and $\max(k, -(k+1)) \leq m \leq N - 2 - \max(k, -(k+1))$.

Defining

$$(67) \quad a_1 + b_1 = c_1,$$

$$(68) \quad a_2 + b_2 = c_2,$$

$$(69) \quad a_1 - b_1 = d_1,$$

$$(70) \quad a_2 - b_2 = d_2,$$

we can show

$$(71) \quad A_{x,y}^{II}(k, \alpha) = e^{j(c_1(k+\frac{1}{2})+\frac{1}{2}d_2(k+\frac{1}{2})^2)} \sum_{m=\max(k, -(k+1))}^{N-2-\max(k, -(k+1))} e^{j((d_1+c_2(k+\frac{1}{2})+2\alpha)(m+\frac{1}{2})+\frac{1}{2}d_2(m+\frac{1}{2})^2)},$$

$$\text{for } -\text{floor}\left(\frac{N}{2}\right) \leq k \leq \text{floor}\left(\frac{N-2}{2}\right).$$

Special Case $d_2 = 0$

$$(72) \quad A_{x,y}^{II}(k, \alpha) = \begin{cases} e^{jc_1(k+\frac{1}{2})(N-1-2\max(k, -(k+1)))} & \text{if } d_1 + c_2(k+\frac{1}{2}) + 2\alpha = 0 \bmod \pi \\ e^{jc_1(k+\frac{1}{2})} e^{j[\frac{1}{2}(d_1+c_2(k+\frac{1}{2})+2\alpha)(N-1)]} \left(\frac{\sin[\frac{1}{2}(d_1+c_2(k+\frac{1}{2})+2\alpha)(N-1-2\max(k, -(k+1))]}{\sin[\frac{1}{2}(d_1+c_2(k+\frac{1}{2})+2\alpha)]} \right) & \text{otherwise.} \end{cases}$$

Thus $|A_{x,y}^{II}(k, \alpha)|$ is concentrated along the line $d_1 + c_2(k+\frac{1}{2}) + 2\alpha = 0$ and symmetrically spread about it with respect to α . For a fixed k , the amount of spread with respect to α can be measured by $1/(N-1-2\max(k, -(k+1)))$

The General Case

Although it seems difficult to evaluate $A_{x,y}^{II}(k, \alpha)$ in the general case, by writing

$$(73) \quad A_{x,y}^{II}(k, \alpha) = e^{j(c_1(k+\frac{1}{2})+\frac{1}{2}d_2(k+\frac{1}{2})^2)} e^{j((d_1+\frac{1}{2}d_2(\frac{N-1}{2})+c_2(k+\frac{1}{2})+2\alpha)(\frac{N-1}{2}))} \sum_{m=\max(k, -(k+1))}^{N-2-\max(k, -(k+1))} e^{j((d_1+d_2(\frac{N-1}{2})+c_2(k+\frac{1}{2})+2\alpha)(m-(\frac{N-2}{2}))+\frac{1}{2}d_2(m-(\frac{N-2}{2}))^2)},$$

we can see that $|A_{x,y}^{II}(k, \alpha)|$ is symmetrically spread about the line $d_1 + d_2 \left(\frac{N-1}{2}\right) + c_2(k + \frac{1}{2}) + 2\alpha = 0$ with respect to α . For small d_2 , $|A_{x,y}^{II}(k, \alpha)|$ is concentrated along the same line. For a fixed k , the amount of spread with respect to α will depend on both $(N - 1 - 2 \max(k, -(k+1)))$ and d_2 .

4.3.3 Type-III Cross Ambiguity Function

Recall that the type-III cross ambiguity function $A_{x,y}^{III}(k, \alpha)$ is defined in terms of the type-I and type-II cross ambiguity functions as

$$(74) \quad A_{x,y}^{III}(k, \alpha) = \begin{cases} A_{x,y}^I(k/2, \alpha) & \text{for even } k, \\ A_{x,y}^{II}((k-1)/2, \alpha) & \text{for odd } k. \end{cases}$$

By writing

$$(75) \quad A_{x,y}^{III}(k, \alpha) = e^{j(c_1(\frac{k}{2}) + \frac{1}{2}d_2(\frac{k}{2})^2)} e^{j((d_1 + \frac{1}{2}d_2(\frac{N-1}{2}) + c_2(\frac{k}{2}) + 2\alpha)(\frac{N-1}{2}))} \sum_{m=0}^{N-1-\max(k, -k)} e^{j((d_1 + d_2(\frac{N-1}{2}) + c_2(\frac{k}{2}) + 2\alpha)(m - (\frac{N-1-\max(k, -k)}{2})) + \frac{1}{2}d_2(m - (\frac{N-1-\max(k, -k)}{2}))^2)},$$

we can see that $|A_{x,y}^{III}(k, \alpha)|$ is symmetrically spread about the line $d_1 + d_2 \left(\frac{N-1}{2}\right) + c_2(\frac{k}{2}) + 2\alpha = 0$ with respect to α . For small d_2 , $|A_{x,y}^{III}(k, \alpha)|$ is concentrated along the same line. For a fixed k , the amount of spread with respect to α will depend on both $(N - \max(k, -k))$ and d_2 .

The Special Case $d_2 = 0$

$$(76) \quad A_{x,y}^{III}(k, \alpha) = \begin{cases} e^{jc_1(\frac{k}{2})(N - \max(k, -k))} & \text{if } d_1 + c_2(\frac{k}{2}) + 2\alpha = 0 \bmod \pi, \\ e^{jc_1(\frac{k}{2})} e^{j[\frac{1}{2}(d_1 + c_2(\frac{k}{2}) + 2\alpha)(N-1)]} \left(\frac{\sin[\frac{1}{2}(d_1 + c_2(\frac{k}{2}) + 2\alpha)(N - \max(k, -k))]}{\sin[\frac{1}{2}(d_1 + c_2(\frac{k}{2}) + 2\alpha)]} \right) & \text{otherwise} \end{cases}$$

Thus $|A_{x,y}^{III}(k, \alpha)|$ is concentrated along the line $d_1 + c_2(\frac{k}{2}) + 2\alpha = 0$ and symmetrically spread about it with respect to α . For a fixed k , the amount of spread with respect to α can be measured by $1/(N - \max(k, -k))$.

5. Detecting Targets in Clutter using Smoothed Wigner Distributions

When the Wigner Distribution (WD) of a radar signal, collected by a pulse Doppler High Frequency Surface Wave Radar during the known presence of a target, are displayed, it is virtually impossible to 'see' the target as a distinct line in the time-frequency plane. This was due to the fact that the strength of the background against which the target had to be detected was much larger than the strength of the target, and the sidelobes of the WD of the background and those of the interaction between the background and the target were obscuring the target.

In general, the background against which targets must be detected by a radar will constitute clutter and noise. In the case of High Frequency Surface Wave Radar (HFSWR) used over the ocean, the clutter is due to Bragg scattering from the surface of the ocean [9]. This clutter can be adequately modeled for our purposes by two targets that are each moving with constant radial velocity. One target moves towards the radar and the other moves away from the radar, with the magnitudes of radial velocities being equal. These are called the approaching and receding Braggs. The real radar signal can thus be modeled by three target signals - two of which represent the Braggs - plus noise.

Recall that the WD of a sum of two signals contains cross-terms due to the interaction between the two signals [2]. In the case of two chirp signals, the cross-terms are of an oscillatory nature and located midway between the lines along which the auto-terms are concentrated. The strength of the cross-terms is proportional to the square root of the product of the strengths of the auto terms.

Approximately speaking, the WD of a real radar signal contains three auto-terms due to the Braggs and the target, three cross-terms due to the interactions between the Braggs themselves and the Braggs and the target, and the interactions of the Braggs and the target with the noise. In the vicinity of the auto-term due to the target, the contribution of the other terms are noise-like with amplitudes larger than that of the target's auto-term, thereby obscuring the target.

The target's auto-term can be made clearly visible as a line by smoothing the WD. This smoothing can be realized as a two-dimensional convolution operation. The problem is to choose an appropriate convolution kernel function. In the following sub-section, we present the heuristics of the derivation of a smoothing kernel that was successfully used on the real radar data.

The smoothed WD shows the target as a distinct line that can be detected via a generic line detection method. We propose taking slices at fixed times and doing a peak detection first. Once the target has been detected and a coarse estimation of its velocity made on at least two time slices, the results can be used to obtain the initial velocity and acceleration parameters of the target. The scope of this study was limited to finding an appropriate smoothing kernel. The software developed provides a good testbed for

further experimentation with different choices of kernel functions.

In the case of a Line-of-Sight (LOS) radar used over land, the clutter is due to reflections from the surface of the earth. This clutter can be adequately modeled for our purposes by a stationary target. The general principles outlined in this report for HFSWR can also be applied for an HFLOS (High Frequency Line-of-Sight) radar.

5.1 Heuristics of the Derivation of the Smoothing Kernel

To choose an appropriate kernel function we use our knowledge of the auto- and cross-ambiguity functions of chirp signals as described in the previous section and the fact that the ambiguity function is the two-dimensional Fourier transform of the WD. Since convolution of the WD with a kernel function is equivalent to multiplication of the AF by the two-dimensional Fourier transform of the kernel function, we can choose an appropriate kernel by studying the auto- and cross-ambiguity functions of chirp signals [8].

We start by making some observations on auto- and cross-ambiguity functions of chirp signals. Recall that the AF is a function of the variables time-offset and frequency-offset. In the following, when we refer to the slope and intercept of a line we associate time-offset with x-axis and normalized frequency-offset with y-axis.

- The auto-ambiguity function of a chirp signal is concentrated along a line through the origin, with slope = $-0.5 \times \text{normalized acceleration}$.
- The cross-ambiguity function of two chirp signals with the same acceleration is concentrated along the line with intercept = $-0.5 \times \text{difference in the normalized initial velocities}$, slope = $-0.5 \times \text{normalized acceleration}$.
- The cross-ambiguity function of two chirp signals with differing accelerations is spread about the line with intercept = $-0.5 \times \text{difference in the normalized median velocities}$, slope = $-0.5 \times \text{average of the normalized accelerations}$. The spread is symmetric in the frequency offset dimension about the above line. For small enough difference in the acceleration, the cross-ambiguity function is concentrated along the above line. For large difference in the acceleration, the cross ambiguity function gets smeared in the frequency offset dimension much like the Fourier power spectrum of an accelerating target gets smeared when the acceleration is large.

Based on the above we can make the following observations on the AF of an HFSWR signal containing Braggs and one target.

- For targets with (magnitude) acceleration less than Bragg velocity / NumPulsesPerCPI, the regions where the cross-terms between the Braggs are concentrated will not overlap with the region where the target's auto-term is concentrated.

- For targets with (magnitude) median velocity greater than $3 \times$ Bragg velocity, the regions where the cross-terms between the Braggs and the target are concentrated will not overlap with the region where the target's auto-term is concentrated.

Therefore, for targets satisfying the above conditions on the acceleration and the median velocity, we can suppress all cross-terms while preserving the target's auto-term simply by setting the value of the AF to zero over the region

frequency-offset $>$ Bragg velocity -
 $0.5 \times$ Bragg cross term region's width in the frequency-offset dimension

After suppressing the cross-terms on the AF, we can take the two-dimensional Fourier transform to obtain a smoothed WD. A more detailed description and discussion of different methods are given in [8]

5.2 Analysis of Real Radar Data

Real HF radar data was analysed using the Fourier transform method and the type-III Wigner distribution method. The data had been collected by a Pulse Doppler High Frequency Surface Wave Radar that uses a 10-element linear receiving antenna array. The data had been collected during the known presence of a target. The radar carrier frequency is 5 672 MHz and the pulse repetition frequency is 9 17762 Hz. There are ten trials and each trial corresponds to a block of 256 pulses. The detailed description of the radar is given by Chan [9,10]

The results of our analysis are presented in Figures 1-20. The results for the type-III Wigner distribution of the time series containing the aircraft are compared simultaneously with the Fourier transform of the aircraft signal. The results show that whenever the target was detectable by the Fourier method, that is in trials 3, 4 and 8, the target was detectable also by the smoothed type-III Wigner distribution method. For the trials 3, 4 and 8, the aircraft is moving with a constant radial velocity. In the other trials, that is in trials 1, 2 and 5, the target was not detectable by the Fourier method but the target was detectable by the smoothed type-III Wigner distribution method to varying degrees of success. For the trials 1, 2 and 5, the aircraft is moving with a constant radial acceleration. Trails 1, 2 and 5 show that there are limitations and shortcomings to the Fourier transform method to detect accelerating targets because of the phenomenon known as Doppler smearing. On the other hand, the time-frequency analysis has the capability to detect the target, since its resolution abilities are not reduced in the presence of a Doppler signature.

An important contribution of the present work is the use of the type-III WD rather than the type-I WD which has been used by many other researchers. When the type-I WD is used, the range of unambiguously measurable normalized velocities is π . Moreover, targets that are π radians away from the clutter region in the spectral domain will get masked by the clutter and cannot be detected. The type-III WD helps us to overcome these problems. When the type-III WD is used, the range of unambiguously measurable

normalized velocities is 2π , and target that are π radians away from the clutter region can be detected

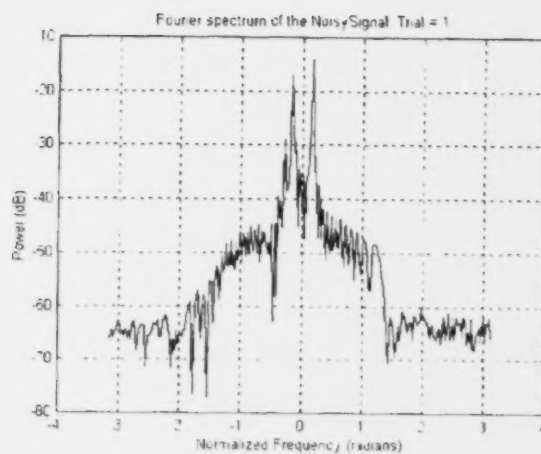


Figure 1: The Fourier transform of the aircraft signal

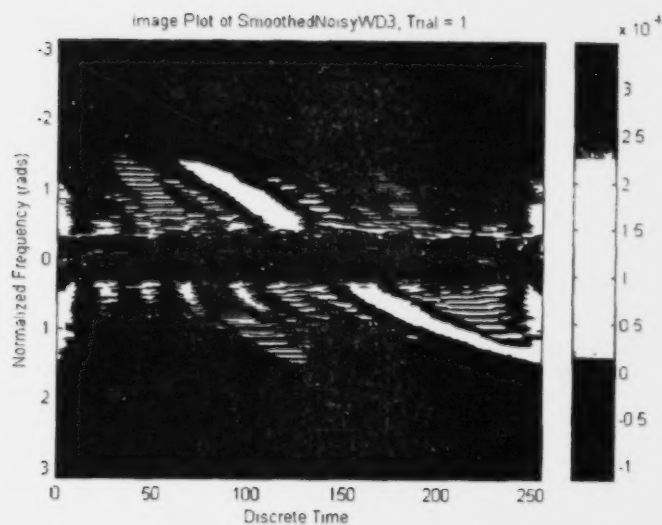


Figure 2: The type-III Wigner distribution of the time series containing the aircraft

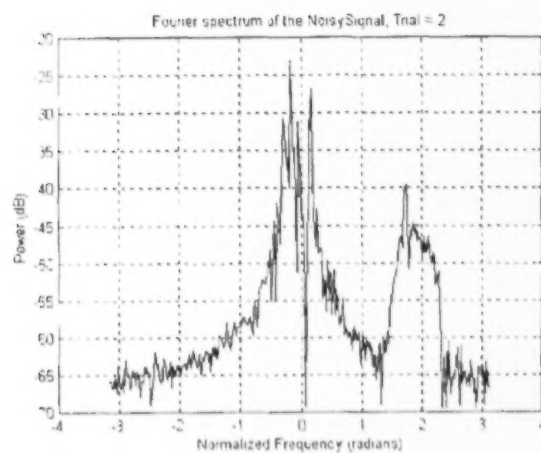


Figure 3: The Fourier transform of the aircraft signal

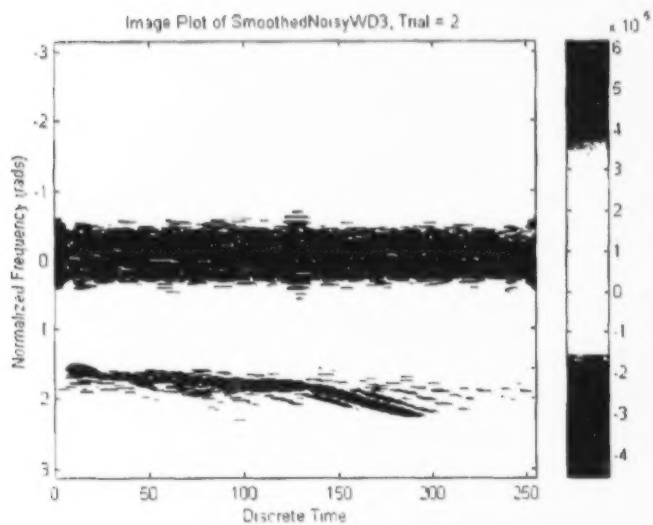


Figure 4: The type-III Wigner distribution of the time series containing the aircraft

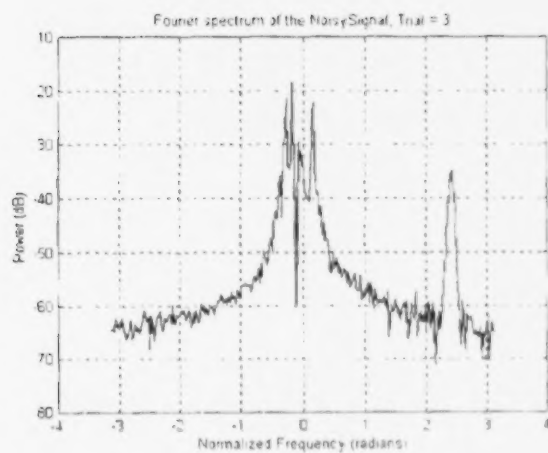


Figure 5: The Fourier transform of the aircraft signal

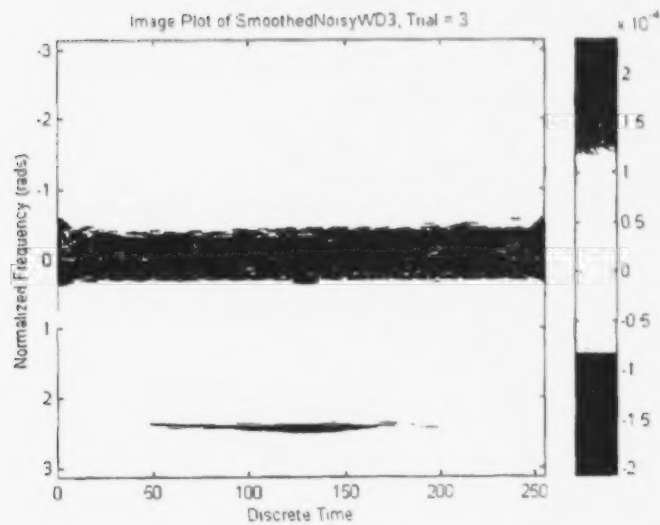


Figure 6: The type-III Wigner distribution of the time series containing the aircraft

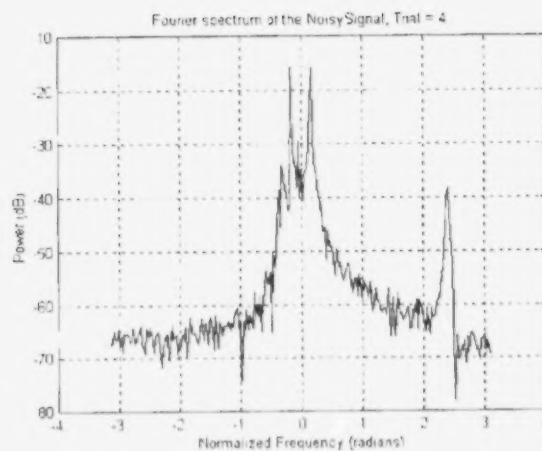


Figure 7: The Fourier transform of the aircraft signal

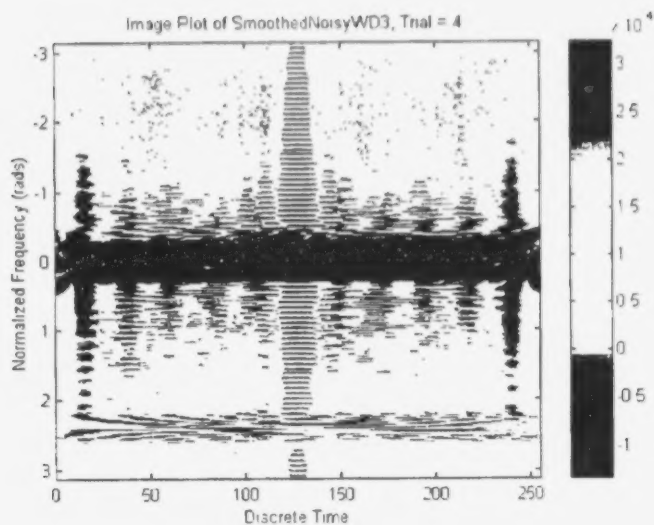


Figure 8: The type-III Wigner distribution of the time series containing the aircraft

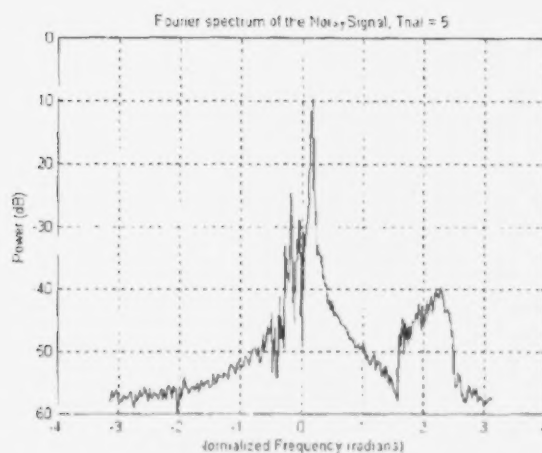


Figure 9: The Fourier transform of the aircraft signal

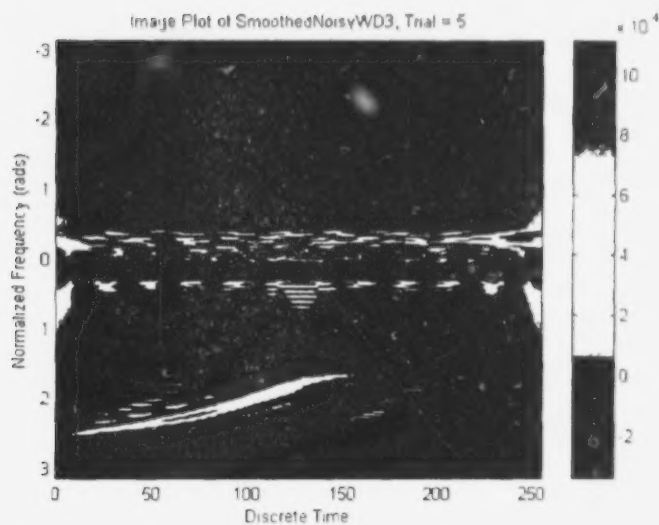


Figure 10: The type-III Wigner distribution of the time series containing the aircraft

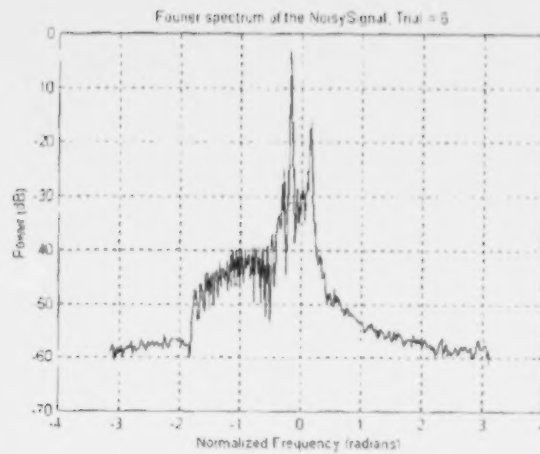


Figure 11: The Fourier transform of the aircraft signal

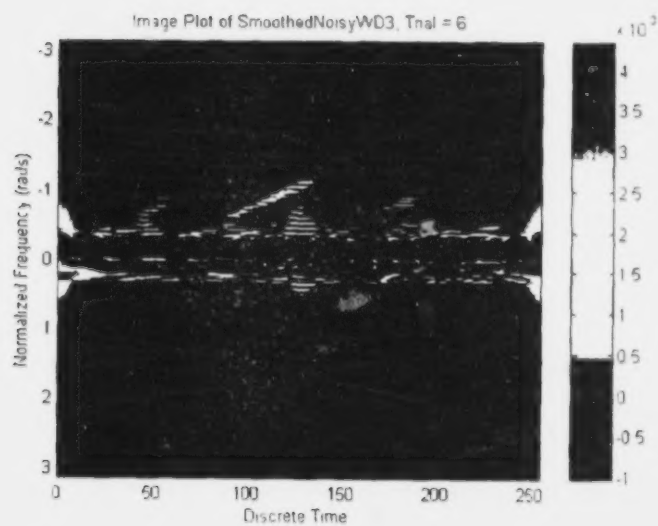


Figure 12: The type-III Wigner distribution of the time series containing the aircraft

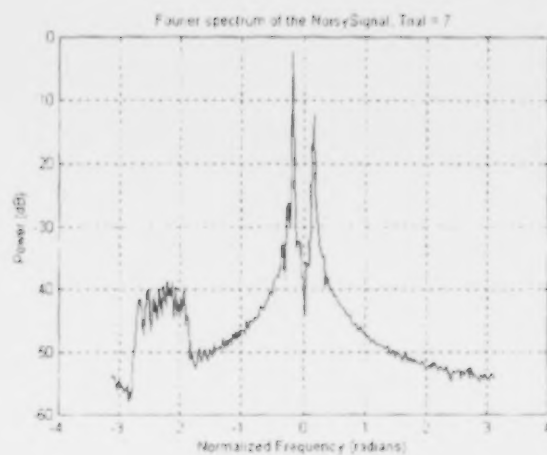


Figure 13: The Fourier transform of the aircraft signal

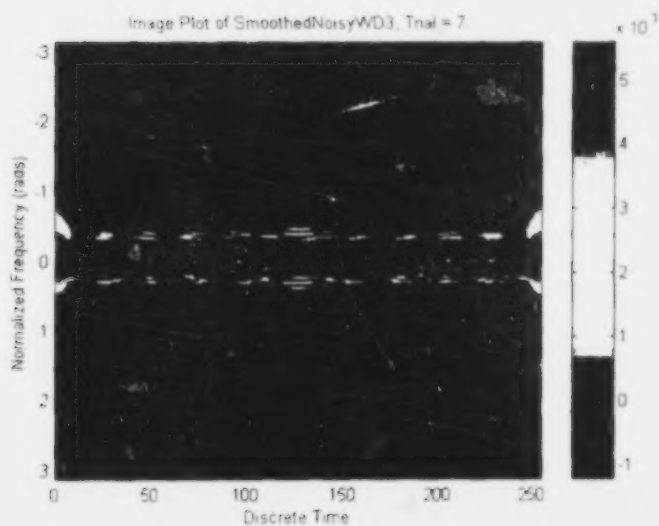


Figure 14: The type-III Wigner distribution of the time series containing the aircraft

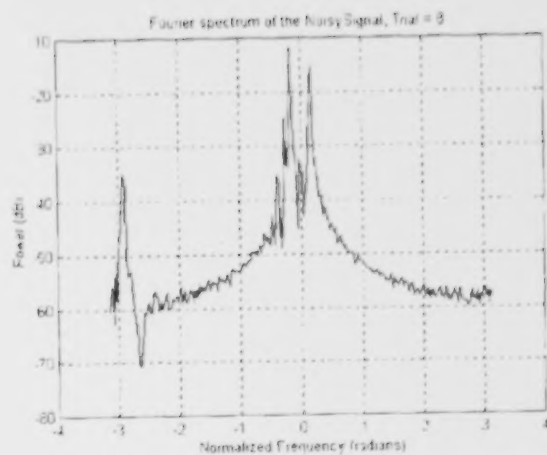


Figure 15: The Fourier transform of the aircraft signal

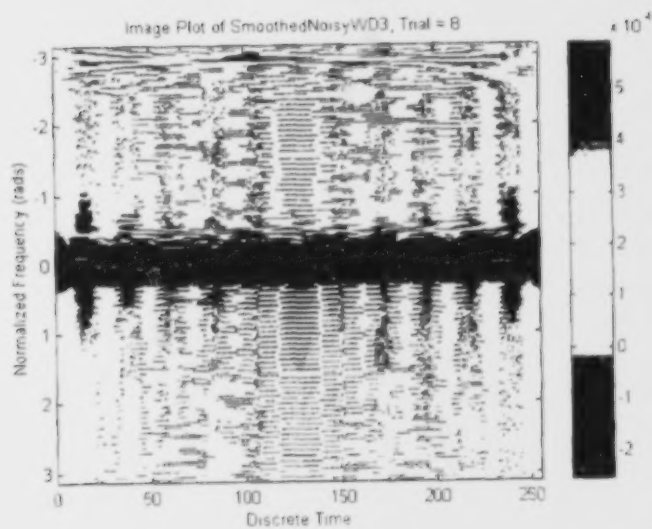


Figure 16: The type-III Wigner distribution of the time series containing the aircraft.

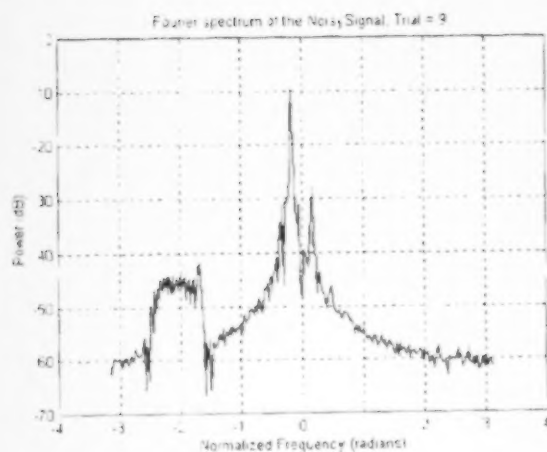


Figure 17: The Fourier transform of the aircraft signal

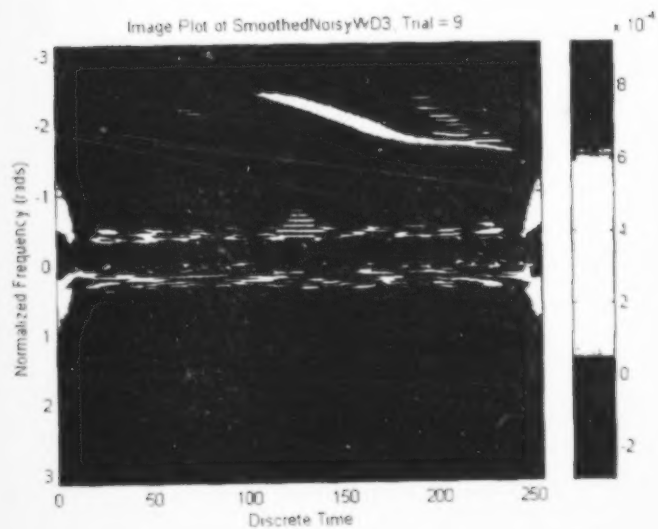


Figure 18: The type-III Wigner distribution of the time series containing the aircraft

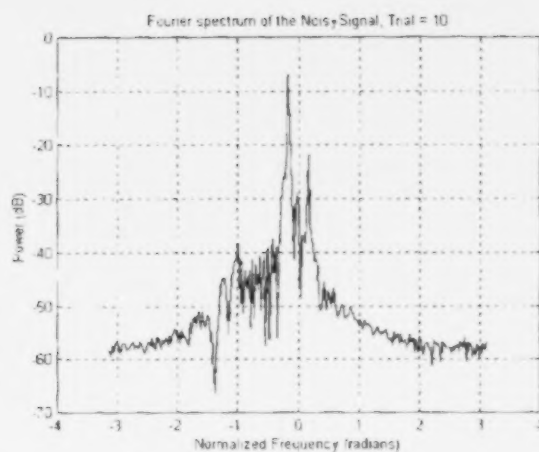


Figure 19: The Fourier transform of the aircraft signal

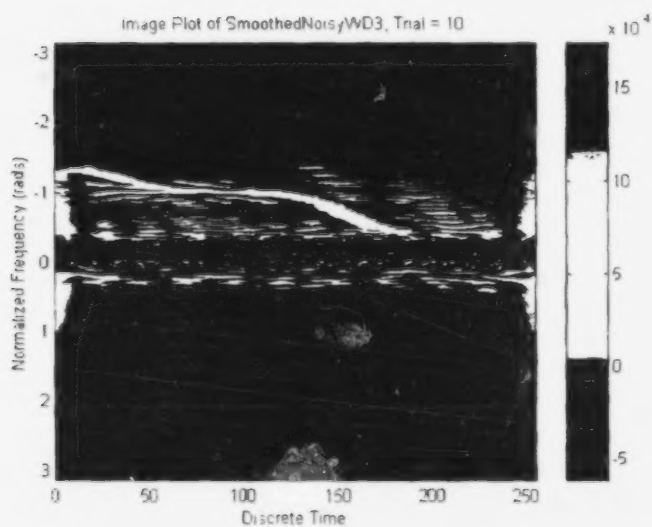


Figure 20: The type-III Wigner distribution of the time series containing the aircraft

6. Conclusion

This report examined the possibility of improving detection of low-altitude aircraft using High Frequency Surface Wave Radar. Because we are dealing with high speeds and accelerations, the time-frequency analysis has the capability to improve the detection, since its resolution abilities are not reduced in the presence of a spread Doppler signature.

The method involved use of the Wigner distribution, together with an ambiguity function. The results demonstrated superior performance for all cases considered. Although the Wigner distribution has for a long time been known to possess interesting properties, its success in solving actual signal analysis problems has been limited. The Wigner distribution has been generally used as a signal interpretation tool only. The study has employed the Wigner distribution for solving a particularly challenging problem, demonstrating that use of time-frequency analysis can improve detection performance.

The results show that whenever the target was detectable by the Fourier transform method, the target was detectable also by the smoothed type-III Wigner distribution method. In the other trials the target was not detectable by the Fourier transform method but the target was detectable by the smoothed type-III Wigner distribution method to varying degrees of success.

Another important contribution of the present work is the use of the type-III Wigner distribution rather than the type-I Wigner distribution which has been used by many other researchers. When the type-I Wigner distribution is used, the range of unambiguously measurable normalized velocities is π . Moreover, targets that are π radians away from the clutter region in the spectral domain will get masked by the clutter and cannot be detected. The type-III Wigner distribution helps us to overcome these problems. When the type-III Wigner distribution is used, the range of unambiguously measurable normalized velocities is 2π , and targets that are π radians away from the clutter region can be detected.

Annex A

The Wigner Distributions of a Discrete-Time Chirp Signal

In this appendix we derive the type-I, type-II, and type-III Wigner distributions for the discrete-time chirp signal

$$(A.1) \quad s(n) = \begin{cases} e^{j(b_1 n + \frac{1}{2} b_2 n^2)} & \text{if } 0 \leq n \leq (N-1) \\ 0 & \text{otherwise} \end{cases}$$

A.1 Type-I Wigner Distribution

Recall that the type-I Wigner distribution $W_s^I(n, \theta)$ is defined as

$$(A.2) \quad W_s^I(n, \theta) = \sum_k s(n+k) s^*(n-k) e^{-j2k\theta},$$

where n is integer-valued and θ is real-valued

It is easy to see that the signal product term $s(n+k)s^*(n-k)$ is zero outside the ranges $0 \leq n \leq (N-1)$ and $-\min(n, N-1-n) \leq k \leq \min(n, N-1-n)$. Thus $W_s^I(n, \theta) = 0$ outside $0 \leq n \leq (N-1)$

Denote

$$(A.3) \quad l = \min(n, N-1-n) = \begin{cases} n & \text{if } n < (N-1)/2, \\ (N-1)/2 & \text{if } N \text{ is odd and } n = (N-1)/2, \\ N-1-n & \text{if } n > (N-1)/2. \end{cases}$$

In terms of this, for $0 \leq n \leq (N-1)$,

$$(A.4) \quad W_s^I(n, \theta) = \sum_{k=-l}^l e^{j(b_1(n+k) + \frac{1}{2} b_2(n+k)^2)} e^{-j(b_1(n-k) + \frac{1}{2} b_2(n-k)^2)} e^{-j2k\theta},$$

$$(A.5) \quad = \sum_{k=-l}^l e^{j(b_1 2k + \frac{1}{2} b_2 4nk)} e^{-j2k\theta},$$

$$(A.6) \quad = \sum_{k=-l}^l e^{-j(\theta - (b_1 + b_2 n))2k},$$

which is a sum of a geometric series that can be easily evaluated

We first observe that the sum can be written as

$$(A\ 7) \quad \sum_{k=-l}^l e^{-j\alpha k},$$

where $\alpha = 2(\theta - (b_1 + b_2 n))$ and then evaluate it to be

$$(A\ 8) \quad \sum_{k=-l}^l e^{-j\alpha k} = \begin{cases} 2l + 1 & \text{if } \alpha = 0 \bmod 2\pi, \\ \frac{\sin[\alpha(l + \frac{1}{2})]}{\sin(\frac{\alpha}{2})} & \text{otherwise.} \end{cases}$$

Thus, for $0 \leq n \leq (N - 1)$,

$$(A\ 9) \quad W_s^I(n, \theta) = \begin{cases} 2 \min(n, N - 1 - n) + 1 & \text{if } \theta = b_1 + b_2 n \bmod \pi, \\ \frac{\sin[(\theta - (b_1 + b_2 n))(2 \min(n, N - 1 - n) + 1)]}{\sin[\theta - (b_1 + b_2 n)]} & \text{otherwise.} \end{cases}$$

A.2 Type-II Wigner Distribution

Recall that the type-II Wigner distribution $W_s^{II}(n, \theta)$ is defined as

$$(A.10) \quad W_s^{II}(n, \theta) = \sum_k s(n + k + 1) s^*(n - k) e^{-j(2k+1)\theta},$$

where n is integer-valued and θ is real-valued

It is easy to see that the signal product term $s(n + k + 1) s^*(n - k)$ zero outside the ranges $0 \leq n \leq (N - 2)$ and $-\min(n + 1, N - 1 - n) \leq k \leq \min(n, N - 2 - n)$. Thus $W_s^{II}(n, \theta) = 0$ outside $0 \leq n \leq (N - 2)$

Denote

$$(A\ 11) \quad l = \min(n, N - 2 - n) = \begin{cases} n & \text{if } n < (N - 2)/2, \\ (N - 2)/2 & \text{if } N \text{ is even and } n = (N - 2)/2, \\ N - 2 - n & \text{if } n > (N - 2)/2. \end{cases}$$

In terms of this, for $0 \leq n \leq (N - 2)$,

$$W_s^{II}(n, \theta) = \sum_{k=-(l+1)}^l e^{j(b_1(n+k+1) + \frac{1}{2}b_2(n+k+1)^2)} e^{-j(b_1(n-k) + \frac{1}{2}b_2(n-k)^2)} e^{-j(2k+1)\theta},$$

(A 12)

$$(A 13) \quad = \sum_{k=-(l+1)}^l e^{j(b_1(2k+1) + \frac{1}{2}b_2(4nk+2n+2k+1))} e^{-j(2k+1)\theta},$$

$$(A 14) \quad = \sum_{k=-(l+1)}^l e^{-j(\theta - (b_1 + \frac{1}{2}b_2 + b_2n))(2k+1)},$$

$$(A 15) \quad = e^{-j(\theta - (b_1 + \frac{1}{2}b_2 + b_2n))} \sum_{k=-(l+1)}^l e^{-j(\theta - (b_1 + \frac{1}{2}b_2 + b_2n))2k},$$

which is a scaled version of a sum of a geometric series that can be easily evaluated

We first observe that the sum can be written as

$$(A 16) \quad \sum_{k=-(l+1)}^l e^{-j\alpha k},$$

where $\alpha = 2(\theta - (b_1 + \frac{1}{2}b_2 + b_2n))$ and then evaluate it to be

$$(A 17) \quad \sum_{k=-(l+1)}^l e^{-j\alpha k} = \begin{cases} 2l+2 & \text{if } \alpha = 0 \bmod 2\pi, \\ e^{j\frac{\alpha}{2}} \left(\frac{\sin[\alpha(l+1)]}{\sin(\frac{\alpha}{2})} \right) & \text{otherwise} \end{cases}$$

Now, introducing the scaling factor, we see that

$$(A 18) \quad e^{-j\frac{\alpha}{2}} \sum_{k=-(l+1)}^l e^{-j\alpha k} = \begin{cases} e^{-j\frac{\alpha}{2}} (2l+2) & \text{if } \alpha = 0 \bmod 2\pi, \\ \frac{\sin[\alpha(l+1)]}{\sin(\frac{\alpha}{2})} & \text{otherwise} \end{cases}$$

$$(A 19) \quad = \begin{cases} (2l+2) & \text{if } \frac{\alpha}{2} = 0 \bmod 2\pi, \\ -(2l+2) & \text{if } \frac{\alpha}{2} = \pi \bmod 2\pi, \\ \frac{\sin[\alpha(l+1)]}{\sin(\frac{\alpha}{2})} & \text{otherwise} \end{cases}$$

Thus, for $0 \leq n \leq (N-2)$,

$$W_s^{II}(n, \theta) = \begin{cases} 2 \min(n, N-2-n) + 2 & \text{if } \theta = b_1 + \frac{1}{2}b_2 + b_2n \bmod 2\pi, \\ -(2 \min(n, N-2-n) + 2) & \text{if } \theta = \pi + b_1 + \frac{1}{2}b_2 + b_2n \bmod 2\pi, \\ \frac{\sin[(\theta - (b_1 + \frac{1}{2}b_2 + b_2n))(2 \min(n, N-2-n) + 2)]}{\sin[\theta - (b_1 + \frac{1}{2}b_2 + b_2n)]} & \text{otherwise.} \end{cases}$$

(A 20)

It is useful to write this as

$$W_s^{II}(n, \theta) = \begin{cases} 2 \min(n + \frac{1}{2}, N-1 - (n + \frac{1}{2})) + 1 & \text{if } \theta = b_1 + b_2(n + \frac{1}{2}) \bmod 2\pi, \\ -[2 \min(n + \frac{1}{2}, N-1 - (n + \frac{1}{2})) + 1] & \text{if } \theta = \pi + b_1 + b_2(n + \frac{1}{2}) \bmod 2\pi, \\ \frac{\sin[(\theta - (b_1 + b_2(n + \frac{1}{2}))) (2 \min(n + \frac{1}{2}, N-1 - (n + \frac{1}{2})) + 1)]}{\sin[\theta - (b_1 + b_2(n + \frac{1}{2}))]} & \text{otherwise.} \end{cases}$$

(A.21)

A.3 Type-III Wigner Distribution

Recall that the type-III Wigner distribution $W_s^{III}(n, \theta)$ is defined in terms of the type-I and type-II Wigner distributions as

$$(A.22) \quad W_s^{III}(n, \theta) = \begin{cases} W_s^I(n/2, \theta) & \text{for even } n, \\ W_s^{II}((n-1)/2, \theta) & \text{for odd } n. \end{cases}$$

For n even and $0 \leq n \leq 2(N-1)$.

$$W_s^{III}(n, \theta) = \begin{cases} 2 \min(\frac{n}{2}, N-1 - \frac{n}{2}) + 1 & \text{if } \theta = b_1 + \frac{1}{2}b_2n \bmod \pi, \\ \frac{\sin[(\theta - (b_1 + \frac{1}{2}b_2n))(2 \min(\frac{n}{2}, N-1 - \frac{n}{2}) + 1)]}{\sin[\theta - (b_1 + \frac{1}{2}b_2n)]} & \text{otherwise.} \end{cases}$$

(A.23)

For n odd and $0 \leq n \leq 2(N-1)$.

$$W_s^{III}(n, \theta) = \begin{cases} 2 \min(\frac{n}{2}, N-1 - \frac{n}{2}) + 1 & \text{if } \theta = b_1 + \frac{1}{2}b_2n \bmod 2\pi, \\ -[2 \min(\frac{n}{2}, N-1 - \frac{n}{2}) + 1] & \text{if } \theta = \pi + b_1 + \frac{1}{2}b_2n \bmod 2\pi, \\ \frac{\sin[(\theta - (b_1 + \frac{1}{2}b_2n))(2 \min(\frac{n}{2}, N-1 - \frac{n}{2}) + 1)]}{\sin[\theta - (b_1 + \frac{1}{2}b_2n)]} & \text{otherwise.} \end{cases}$$

(A 24)

Combining the above, for all $0 \leq n \leq 2(N-1)$.

$$\begin{aligned}
 W_s^{III}(n, \theta) = & \begin{cases} 2 \min(\frac{n}{2}, N-1-\frac{n}{2}) + 1 & \text{if } \theta = b_1 + \frac{1}{2}b_2n \bmod 2\pi, \\ (-1)^n [2 \min(\frac{n}{2}, N-1-\frac{n}{2}) + 1] & \text{if } \theta = \pi + b_1 + \frac{1}{2}b_2n \bmod 2\pi, \\ \frac{\sin[(\theta - (b_1 + \frac{1}{2}b_2n))(2 \min(\frac{n}{2}, N-1-\frac{n}{2}) + 1)]}{\sin[\theta - (b_1 + \frac{1}{2}b_2n)]} & \text{otherwise.} \end{cases} \\
 \text{(A.25)}
 \end{aligned}$$

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(U) Real radar data has been analysed using the Fourier transform method and the type-III Wigner distribution. The results show that whenever the target was detectable by the Fourier transform method, the target was detectable also by the smoothed type-III Wigner distribution method. In the other trials the target was not detectable by the Fourier transform method but the target was detectable by the smoothed type-III Wigner distribution method to varying degrees of success. Based on the analysis of real radar data, we conclude that the smoothed type-III Wigner distribution provides a promising method of detecting accelerating targets. However, more work has to be done to find an optimum smoothing method. It may turn out that different smoothing methods have to be used depending on the acceleration and the closeness of the target to the clutter region. Another important contribution of the present work is the use of the type-III Wigner distribution rather than the type-I Wigner distribution which has been used by many other researchers.

When the type-I Wigner distribution is used, the range of unambiguously measurable normalized velocities is π . Moreover, targets that are π radians away from the clutter region in the spectral domain will get masked by the clutter and cannot be detected. The type-III Wigner distribution helps us to overcome these problems. When the type-III Wigner distribution is used, the range of unambiguously measurable normalized velocities is 2π , and target that are π radians away from the clutter region can be detected.

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Time-Frequency Analysis
 Discrete-time signal
 Wigner Distribution
 Generalized Likelihood Ratio Test
 Fourier Transform
 Radon Transform
 Instantaneous Frequency
 High-Frequency Radar
 Doppler Processing
 Accelerating Targets
 Doppler Radar
 Doppler Smearing
 Generalized Velocity
 Generalized Acceleration

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